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Aerosol optical properties and their radiative effects in northern China

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[1] As a fast developing country covering a large territory, China is experiencing rapid environmental changes. High concentrations of aerosols with diverse properties are emitted in the region, providing a unique opportunity for understanding the impact of environmental changes on climate. Until very recently, few observational studies were conducted in the source regions. The East Asian Study of Tropospheric Aerosols: An International Regional Experiment (EAST-AIRE) attempts to characterize the physical, optical and chemical properties of the aerosols and their effects on climate over China. This study presents some preliminary results using continuous high-quality measurements of aerosol, cloud and radiative quantities made at the first EAST-AIRE baseline station at Xianghe, about 70 km east of Beijing over a period of one year (September 2004 to September 2005). It was found that the region is often covered by a thick layer of haze (with a yearly mean aerosol optical depth equal to 0.82 at 500 nm and maximum greater than 4) due primarily to anthropogenic emissions. An abrupt ''cleanup'' of the haze often took place in a matter of one day or less because of the passage of cold fronts. The mean single scattering albedo is approximately 0.9 but has strong day-to-day variations with maximum monthly averages occurring during the summer. Large aerosol loading and strong absorption lead to a very large aerosol radiative effect at the surface (the annual 24-hour mean values equals 24 W m^{-2}), but a much smaller aerosol radiative effect at the top of the atmosphere (one tenth of the surface value). The boundary atmosphere is thus heated dramatically during the daytime, which may affect atmospheric stability and cloud formation. In comparison, the cloud radiative effect at the surface is only moderately higher (-41 W m^{-2}) than the aerosol radiative effect at the surface.

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1. Introduction

[2] Aerosols are a major factor influencing the Earth's radiation budget and may also affect the hydrologic cycle. By scattering and absorbing solar radiative energy, aerosols alter the radiation budgets at the top, bottom and interior of the atmospheric column [*Charlson et al.*, 1992], which in turn affects the atmospheric heating rate and stability, further influencing cloud development and microphysics, as well as precipitation [*Hansen et al.*, 1997; *Rosenfeld and Lensky*, 1998; *Kaufman et al.*, 2001; *Ramanathan et al.*, 2001a]. Such impacts of aerosols on the radiation budget are usually referred to as the direct aerosol radiative effect (ARE) and semidirect effect, although aerosol forcing is a term often used particularly for anthropogenic aerosols. Despite a substantial increase in our efforts to further understand aerosols and their climatic effects, aerosol radiative effects remain one of the largest uncertainties in climate studies [*Intergovernmental Panel on Climate Change*, 2001].

[3] To increase understanding of these issues, many recent investigations were committed to improving the global estimation of ARE. At the top of the atmosphere (TOA), estimates of global mean ARE obtained following different methods appear to converge to a value in the neighborhood of -5 W m^{-2} [*Bellouin et al.*, 2005; *Loeb and Manalo-Smith*, 2005; *Remer and Kaufman*, 2005; *Chou et al.*, 2002]. It is worth noting, however, that these estimates were based on satellite retrievals of aerosol optical depth (AOD) from various sensors such as MODIS, TOMS, POLDER, and CERES. It is widely known that satellite AOD retrievals are mainly valid over dark targets such as oceans and vegetated land surfaces, but a few satellite sensors (e.g., MISR, POLDER) are valid over bright land and snow/ice surfaces. In light of the common shortcomings

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suffered by various satellite retrievals, the narrow range of ARE estimates does not necessarily lend enough confidence on the ARE. Also, satellite retrievals of ARE are limited to clear-sky conditions, while the all-sky ARE is also important but more difficult to derive [*Li and Trishchenko*, 2001].

[4] Estimation of the ARE at the surface is as important as that at the TOA. Because of variable aerosol absorption, the surface ARE is larger and more variable than the ARE at the TOA [*Li*, 1998; *Li and Kou*, 1998; *Satheesh and Ramanathan*, 2000]. It is much more challenging to estimate the ARE at the surface because it requires good knowledge of three aerosol variables, namely, the spectral AOD, the aerosol single scattering albedo (SSA) and the asymmetry factor. The latter two are extremely difficult to derive from conventional satellite observations [*King et al.*, 1999; *Kaufman et al.*, 2001, 2002a, 2002b]. To date, most global estimates of ARE at the surface have been made by model simulations of different aerosol species [*Takemura et al.*, 2005; *Liao et al.*, 2004]. Because of inherent model assumptions and error propagation, estimates of surface AREs are prone to considerable uncertainties.

[5] Both satellite-based and model-based estimates of ARE require validation using in situ and ground-based observations. As a result of high spatial and temporal variations in aerosol loading and optical properties, extensive observations need to be carried out in all major aerosol source regions. Ground observation is the most reliable means of estimating the ARE at the surface. Unfortunately, the existing ground-based observation networks such as the Aerosol Robotic Network (AERONET) [*Holben et al.*, 1998] and the Baseline Surface Radiation Network (BSRN) [*Ohmura et al.*, 1998] reside chiefly in developed regions where aerosol loading is generally lower than in developing regions. Fewer high-quality and long-term ground observation stations are located in major aerosol source regions such as the Africa, Asia, and South America. At present, the total number of AERONET sites are 36 in North America, 24 in Europe, but only 18 in Asia, 10 in Africa, 11 in South America, and 16 over all oceanic sites. By contrast, the average AOD observed in the latter two regions are more than twice the value in the former two regions.

[6] As a fast developing and densely populated region in the world, Asia is a major source of aerosols whose loadings are high and chemical/physical properties are complex [*Li*, 2004]. To date, a handful of field experiments have been conducted in Asia such as the Indian Ocean Experiment (INDOEX) [*Ramanathan et al.*, 2001b], the Asian-Pacific Regional Aerosol Characterization Experiment (ACE-Asia) [*Huebert et al.*, 2003], and the Asian Atmospheric Particle Environment (APEX) [*Nakajima et al.*, 2003]. Many important findings were made from these experiments such as the generally strong absorption of Asian aerosols [*Satheesh and Ramanathan*, 2000; *Kim et al.*, 2004], the modification of dust aerosols by air pollutants [*Kim et al.*, 2005], etc. Despite the significant accomplishments achieved by these experiments, a fundamental limitation still exists, namely, that few in situ observations were made in the continental source regions on a continual basis. Except for the short-term operation of some basic measurements made at a few sites in China, substantially more observations must be made in order to portray the spatial and temporal variations of the complex aerosols in the vast territory of China.

[7] To fulfill this goal, the East Asian Study of Tropospheric Aerosols: an International Regional Experiment (EAST-AIRE) has been conducted by American and Chinese scientists since 2004 (Z. Li et al., Preface to special section: Overview of the East Asian Study of Tropospheric Aerosols: An International Regional Experiment (EAST-AIRE), submitted to *Journal of Geophysical Research*, 2006). A primary goal of the study is to acquire aerosol optical, physical and chemical properties and understand their climatic effect through means of ground-based, airborne and space-based observations. The observational component of the study consists of extensive measurements of aerosol, cloud and radiation quantities at 5–6 baseline stations, spectral aerosol loading measurements made at 25 stations as part of China's Ecological Research Network [*Xin et al.*, 2007], and short-term intensive observation campaigns measuring aerosol chemical and physical properties as well as precursor gases on the ground and in the air [*Li et al.*, 2006; *Dickerson et al.*, 2007].

[8] This study makes use of measurements made since September 2004 at the first EAST-AIRE baseline station in Xianghe, China. The observation quantities used in the study are described in section 2. The data are classified as clear-clean, clear-hazy, and cloudy for determining aerosol and cloud radiative effects. The methods of scene identification are introduced in section 3. The aerosol optical properties are discussed in section 4. Section 5 presents the results of aerosol and cloud radiative effects. Conclusions from the study are given in section 6.

6. Summary

[40] As the most populated and fastest developing country in the world, China is a region of heavy aerosol loading with diverse physical, chemical, optical aerosol properties whose climatic influence could be substantial, but remains largely uncertain. Improving the estimate of the global aerosol effect on climate requires a good knowledge and understanding of aerosols in this and many other major source regions. Unfortunately, many of the major aerosol emission regions are severely undersampled. To tackle the problem, an extensive observational program was established in China as a joint scientific endeavor by American and Chinese scientists. One major observation component is the establishment and operation of baseline stations that are fully equipped in conformity with the international BSRN and AERONET networks. The first of a series of planned baseline stations was set up in Xianghe, 70 km southeast of Beijing, in September 2004. The site has provided quality-controlled continual observations of aerosol, cloud and radiation quantities since its establishment. This paper presents some preliminary results based on data collected for an entire year.

[41] The most prominent finding is the high aerosol loading and dramatic changes in AOD from day to day. The annual average AOD is 0.82 with maximum values exceeding 4. The AOD generally increases steadily from a very low background value (less than 0.2) to very large values in a few days (5–10 days) then drops sharply to a very low value in less than one day. The sudden drops were usually caused by changes in air mass due to the passage of cold fronts. The episodic increase of AOD was usually caused by the buildup of anthropogenic pollutants, as indicated by the consistent episodes seen in simultaneous measurements of precursor gases such as SO_2 and CO and NOy available during the IOP in March 2005. The retrieval of the single scattering albedo from a Cimel Sun photometer showed a similar day-to-day fluctuation with a mean value around 0.9. There is a weak seasonal trend with large and small values occurring during the summer and late fall, respectively. The single scattering albedo increases with the AOD, presumably because of an increasing proportion of sulfate aerosols.